RADIO-WAVE PROPAGATION RESEARCH IN THE DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH DURING THE YEARS 1937-46*

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SUMMARY

The fundamental study of the propagation of radio waves has formed an important part of the programme of the Radio Research Board, which was established under the Department of Scientific and Industrial Research in 1920. The object of the present paper is to survey the progress made in this field during the decade ending in 1946, and to indicate the manner in which the investigations concerned have been developed to meet the requirements of those responsible for applying radio waves to various practical uses. The researches described cover the radio-frequency spectrum from about 10 kc/s up to 50 000 Mc/s or more. They deal with the transmission of radio waves along the surface of the earth, and illustrate the manner in which this transmission is influenced by the electrical properties of the ground and the curvature of the earth and by the corresponding properties and slopes of natural and man-made protuberances on the ground. The characteristics of the ionosphere have been studied intensively for over twenty years, and during the past decade considerable advance has been made in our knowledge of this region of the atmosphere and of the manner in which radio waves are propagated through it. With the advance of radio technique and developments to shorter and shorter wavelengths, it has become clear that wave propagation in the lower atmosphere is greatly affected by the vertical gradient of the temperature and humidity of the air; the associated phenomena have been studied directly, and, in addition, the electrical properties of the constituents of the atmosphere, solid, liquid and gaseous, have been determined at the very high radio frequencies relevant to this portion of the investigation. Finally, the important part played by radio noise of either atmospheric or extraterrestrial origin has been studied with a view to understanding more clearly the manner and circumstances in which such noise can either influence the successful transmission of intelligence by radio waves, or provide a means of increasing our knowledge of such phenomena as those associated with thunderstorms and activity on the surface of the sun. This survey attempts to show what an important part the study of wave propagation plays in numerous applications of radio technique, and demonstrates that there is still much further work to be done before the full requirements of those using the technique can be met in a satisfactory manner.

(1) INTRODUCTION

Before electromagnetic waves can be used successfully for the transmission of intelligence from one point to another, it is necessary to understand quite thoroughly the mode of propagation of the waves between the sending and receiving stations. The choice of frequency, radiated power and, to some extent, the nature of the aerial to be used at the sending station depend largely upon the wave-propagation conditions prevailing over the particular transmission path at the time and season of the communication. At the receiving station, the equipment including the aerial system must be capable of detecting the incoming signals clear of the background of radio noise. This background noise is, also, partly dependent upon the wave-propagation conditions prevailing over the path at the time of transmission. It is well known among radio engineers to-day that, however efficient may be the sending and receiving equipment, intelligence, whether this be telegraphy, telephony, radar or navigational information, cannot be communicated unless the propagation conditions are suitable. The study of radio-wave propagation is thus seen to be fundamental to the whole of radio-engineering technique, and it is on this account that it has formed an important part of the programme of the Radio Research Board that was established under the Department of Scientific and Industrial Research in 1920. The object of this paper is to review the contribution made by the Board to the present state of knowledge of this subject during the decade 1937–46. The complete study of radio-wave propagation brings in its train a large number of other subjects, such as the development of methods of measuring frequency, power, field strength, waveform, polarization, and direction of travel, and such measurements in their turn involve the development and application of a wide range of modern electronic techniques using the most advanced types of valves, cathode-ray oscillographs and their associated circuits. As the field of radio applications has advanced towards increasingly higher frequencies, the demand for a knowledge of wave-propagation conditions has progressed correspondingly, and to-day the study of these conditions ranges over the whole of the radio-frequency spectrum from about 10 kc/s up to 50 000 Mc/s or more. While much has been learned in this field during the past half-century, there is still much virgin soil to be turned before the full requirements of the radio engineers and operators can be met in a satisfactory manner.

As is well known to-day, a variety of phenomena determine the mode of transmission of radio waves between a sending and receiving station. The electrical characteristics of the surface of the earth determine the coefficient of reflection for waves incident upon it; at the same time these waves are diffracted round the curved surface of the earth or of any hills or other protuberances upon it. Such protuberances, whether natural or man-made, also absorb or reflect the energy of the waves to an extent depending upon the wavelength of the radiation and on the properties of the obstructing objects.

When radio waves or frequencies below about 30 Mc/s are transmitted through the lower atmosphere clear of the earth's surface they travel substantially under "free-space conditions" in straight lines, and are, for practical purposes, unaffected by the vertical gradients of the refractive index of the atmosphere. As the frequency is increased, however, the waves become susceptible to refraction in the lower atmosphere, and even to total reflection in cases where the angle of incidence and the gradient of meteorological conditions are appropriate. Recent work has shown that these phenomena become of increasing importance as the frequency of the waves is increased up to the highest limits at present in practical use—about 50 000 Mc/s.

It has long been known that the waves of frequencies below 30 Mc/s are reflected by the ionized regions of the upper atmosphere, the ionosphere, which is located between 50 and 400 km above the surface of the earth. The achievements of long-distance radio communication covering ranges up to the circum-

* Radio Section paper. Official communication from the National Physical Laboratory.

ference of the earth are entirely the result of the transmission of these waves in the space between the earth's surface and the ionosphere, and much intensive study of the characteristics of the ionosphere and of the transmission of waves through it has taken place during the past quarter of a century.

Although a considerable groundwork of knowledge had been built up prior to 1937, the past decade has seen a vast increase in the breadth and intensity of the research effort devoted to the subject of radio-wave propagation, and the following sections contain a brief survey of the nature and results of this effort in the D.S.I.R. in this country. This work has been supplemented by other investigations, some of a theoretical nature and others of a practical nature more closely associated with radio communication, conducted by other British organizations, but these have been excluded from the present survey.

(2) GROUND-WAVE PROPAGATION

The investigations conducted by the D.S.I.R. during the past ten years on the propagation of radio waves along the ground have been almost entirely confined to a study of the phenomena occurring at frequencies between about 30 and 3 000 Mc/s (wavelengths from about 10 m down to 10 cm). The effects of frequency and wave polarization on the propagation characteristics have been explored both for the case in which the receiver is within visible range of the sender, and for that in which the receiver is beyond the visible horizon so that the transmission conditions are subject to diffraction of the waves. The electrical properties of the ground have been measured, and their effect on the reflection coefficient of radio waves in the above frequency range has been determined. An experimental study has also been made of the attenuation of such waves produced by trees and buildings in the transmission path.

(2.1) Sender and Receiver within Optical Range

An experimental investigation by McPetrie and Saxton[1] of the transmission of 2- and 3-m waves over land has shown that, provided the received signal is not modified by diffraction, the propagation characteristics of horizontally and vertically polarized waves are identical for a range of sender and receiver heights which are large compared with the wavelength, but small compared with the distance of transmission. Subject to these conditions, the field strength $\mathscr{E}$ at a distance d metres, on a plane earth, from a half-wavelength dipole radiating P watts is given by

$$\mathscr{E} = 90 h_T h_R \sqrt{P/\lambda d^2} \text{ V/m} \quad . \quad . \quad . \quad . \quad (1)$$

in which h_T = height of transmitter in metres, h_R = height of receiver in metres, λ = wavelength in metres.

This relation results from the combination of the direct ray from the transmitter to the receiver and a ray reflected from the earth, assuming that the reflection coefficient is -1.

If the curvature of the earth is taken into account, the right-hand side of equation (1) must be multiplied by a factor

$$F \left[1 - \frac{h_T d^2}{2R(h_T - h_R)^2}\right]\left[1 - \frac{h_R d^2}{2R(h_T - h_R)^2}\right] \quad . \quad (2)$$

in which R is the radius of the earth in metres. A divergence factor, D, should be included also to take into account the fact that a cone of radiation has a greater angle after reflection at the earth's convex surface than it has on incidence. Thus $D < 1$, but if the distance of transmission is not greater than about half the horizon distance corresponding to the higher terminal point, then the difference of D from unity may be neglected. It may be mentioned that normal refraction in the earth's atmosphere may be allowed for by using an effective radius $R' \simeq \frac{4}{3}R$ in relation (2), and further reference to such atmospheric refraction effects will be made in a later section of the paper.

The results of the experiments referred to above showed good agreement with those deduced from equation (1), as illustrated in Fig. 1, in which the ground contour over the path of the

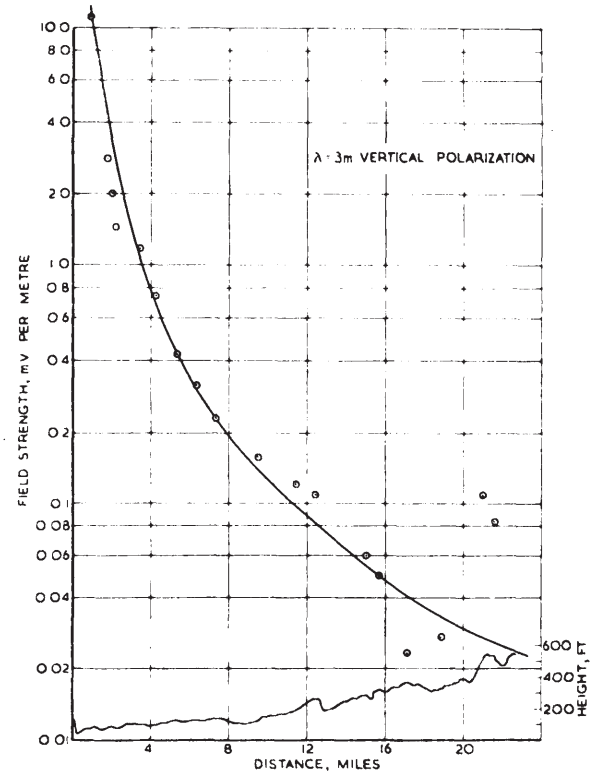

Fig. 1.—Graph showing field strength in N.W. direction plotted against distance.
Teddington transmitter.

measurements is also shown. The fact that the agreement is so good at distances up to as much as 25 km is probably due to the fact that the ground rises steadily from the transmitter in a manner tending to compensate for the curvature of the earth. In these observations the sender and receiver heights were about 20 m and 5 m respectively. The similarity of the propagation of horizontally and vertically polarized waves at a wavelength of 2 m is demonstrated in Fig. 2, which illustrates results obtained with transmissions from an aerial at Brookmans Park some 70 m above ground level, the receiving aerial being at a height of 5 m as before. All these observations provide good justification for the assumption that, at such wavelengths, the reflection coefficient of the earth is -1 for both horizontally and vertically polarized waves.

(2.2) The Diffracted Field

Differences in the propagation characteristics of horizontally and vertically polarized waves in the metre waveband begin to appear when the conditions are such that diffraction of the waves over a curved earth surface becomes important. The first experiments of this nature[2] were made on a ridge of Dunstable Downs with a wavelength of 3 m (100 Mc/s). The results indicated that, for equal initial intensity, radiation polarized with the electric vector vertical was stronger in the shadow than radiation polarized horizontally. It was realized that this phenomenon was similar to that obtained with light waves when diffraction occurs at the edge of an obstacle of conducting material. Furthermore, in the optical case, in the region of the

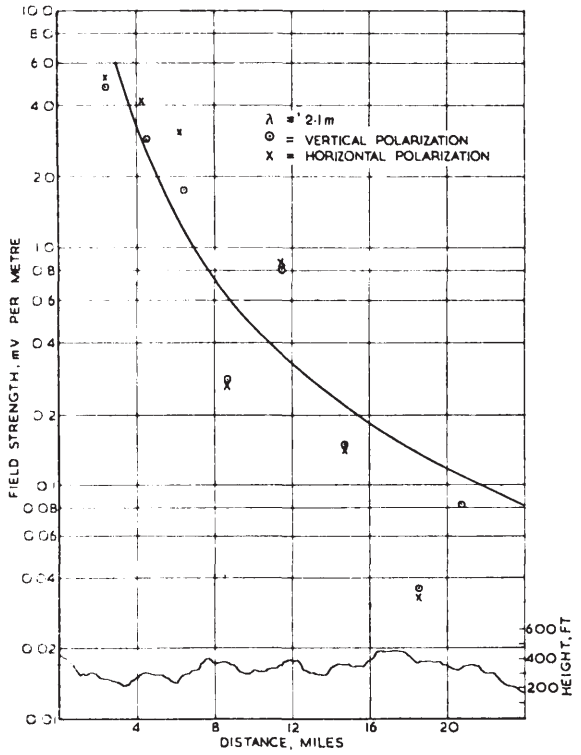

Fig. 2.—Comparison of propagation of horizontally and vertically polarized waves.
Brookmans Park transmitter.

diffracted field just outside the shadow, radiation polarized with the electric vector parallel to the diffracting edge is more intense than radiation polarized perpendicular to the edge. Experiments conducted at a suitable site on the South Downs,[2] the contour of which is depicted in Fig. 3, proved that a similar state of affairs

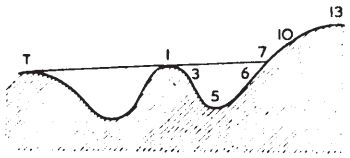

Fig. 3.—Contour of site of diffraction experiments on the South Downs.
(See results in Table 1.)

occurred with radio waves of 3-m wavelength. Table 1 indicates the type of result obtained in measurements made at a series of positions progressing steadily from 1 to 13 (Fig. 3).

This work was later extended by McPetrie and Ford,[3] who investigated experimentally the propagation of radio waves over smooth hills or bare ridges using wavelengths between 10 cm and 10 m (30–3 000 Mc/s). These experiments confirmed and extended the earlier results obtained at the wavelength of 3 m. At wavelengths below 50 cm there was found to be no observable difference between the behaviour of vertically and horizontally polarized waves under the conditions of the experiments. For wavelengths lying roughly between 50 cm and 5 m, vertical polarization gave stronger signals inside the shadow region, and the field with horizontally polarized waves was stronger just outside this region. At still longer wavelengths, vertical polarization gave stronger signals both inside and outside the shadow, but the difference between the two polarizations was greatest inside the shadow and least outside it. Furthermore, when using horizontal polarization over the wavelength range 10 cm–

Table 1

Observation position	Field-strength in mV/m		Ratio of vertical to horizontal fields	Remarks (Ref. Fig. 3)
	Vertical polarization	Horizontal polarization		
1	32·0	31·0	1·03	in shadow
2	6·3	4·1	1·54	
3	2·5	0·95	2·63	
4	1·2	0·5	2·40	
5	1·1	0·5	2·04	
6	1·9	1·4	1·36	
7	7·9	8·4	0·94	outside shadow
8	9·8	11·5	0·85	
9	12·0	19·7	0·61	
10	9·8	17·5	0·56	
11	6·5	9·8	0·66	
12	2·0	2·2	0·90	
13	0·75	0·7	1·04	

10 m it was found that the rate of attenuation of received signal with distance in the shadow of the ridge was in excellent agreement with the theoretical diffraction analysis of Domb and Pryce.[4] This analysis is based on the use of a reflection coefficient of — 1, which thus applies at large angles of incidence for horizontally polarized waves in the above wavelength range, and is therefore in complete agreement with the results of the work described above.

With a view to ascertaining the effects of various obstacles such as trees and buildings, McPetrie and Ford[5] made observations on the propagation of radiation of 9-cm wavelength. It was found that thin screens of leafless trees, wooden-framed windows, a tile or slate roof, and the side of a light wooden hut produced an attenuation of the waves of less than 10 db. Most other obstacles, including stone buildings, produced such a high attenuation that, for radiation of 9-cm wavelength, they must be regarded as opaque objects behind which the field is entirely due to diffraction.

(2.3) Electrical Properties of the Ground

In cases where ultra-short-wave radiation—particularly if vertically polarized—is not incident to the ground at a grazing angle, the reflection coefficient cannot be taken as equal to — 1, but is a function of the permittivity and conductivity of the ground. Also, if the aerials are close to the ground, the resultant field at the receiving point cannot be regarded simply as the combination of a direct and a reflected wave, but the surface wave must also be considered. Under these conditions it is therefore necessary to know the electrical properties of the ground.

Prior to 1937 staff of the National Physical Laboratory had made several investigations of the electrical properties of various types of ground and of fresh water and sea water over a frequency range from 50 c/s to some 60 Mc/s. One of the methods described by McPetrie[6] has recently been used for such determinations at wavelengths of 2 and 5 m by McPetrie and Saxton.[7] The measurements involved the delineation of the interference pattern produced between the direct and reflected waves above the ground with an elevated transmitter. Theoretically it should be possible to determine both the permittivity and the conductivity of the ground from observations of the positions and magnitudes of the maxima and minima of the standing waves. In practice, for the radio frequencies and electrical constants concerned, it is possible to determine only the permittivity with reasonable accuracy by this means, for the determination of the conductivity involves the accurate measurement of a

very small angle which is not as easily achieved as is the measurement of the amplitude of the standing waves. This difficulty in measuring the conductivity arises because, for the values usually found for soil, the reflection coefficient for wavelengths of the order of a few metres is determined largely by the value of the permittivity. In order to obtain a more reliable value for the conductivity, measurements were made of the absorption of 2- and 5-m waves in direct transmission through soil between a sender and receiver buried in the ground a short distance apart. The results of such measurements combined with reflection observations on the same site enabled both the permittivity and conductivity to be more precisely determined.

Experiments were made at frequent intervals over a period of a year, on a sandy loam site at the National Physical Laboratory, Teddington, to ascertain the range of variation of ground constants with weather conditions. It was found that, during the period concerned, the year 1941, the permittivity varied between 5 and 25 e.s.u., and the conductivity varied from just under 10^8 e.s.u. to $4 \cdot 10^8$ e.s.u., the highest values of both permittivity and conductivity occurring after periods of heavy and continuous rain.

Ford and Oliver[8] have recently explored the reflecting properties of several types of ground surface, and also of a 4% salt solution (approximating to sea water) for radiation of wavelength 9 cm, and at angles of incidence between 45° and 80°. Measurements were also made of the absorption of 9-cm waves in the media concerned, and these, combined with the reflection-coefficient observations, provided the necessary data for the determination of the permittivities and conductivities of wet and dry soil, of tap water, and of the 4% salt solution. Table 2 shows the values obtained.

Table 2

Medium	Permittivity, e.s.u.	Conductivity, e.s.u.
Dry sand loam	2	$3 \cdot 10^8$
Sand loam saturated with water	24	$6 \cdot 10^9$
Tap water	75–80	$2 \cdot 10^{10}$
4% salt solution (≃ sea water)	75–80	$5{\cdot}5 \cdot 10^{10}$

Specular reflection of 9-cm waves was found to occur only at very smooth surfaces, and, under practical conditions, the presence of vegetation would preclude such reflection, except possibly at grazing incidence. If $h \cos \theta \simeq 0{\cdot}2\lambda$, where h is the depth of surface irregularities and θ is the angle of incidence, then the reflection coefficient is about half that for specular reflection at the same medium: if $h \cos \theta > 0{\cdot}5\lambda$ the reflection coefficient is unlikely to exceed 0·1 for any polarization or angle of incidence.

To facilitate the application of theory to practical cases of reflection from the ground or other surfaces, curves based upon Fresnel's equations have been prepared by McPetrie,[9] in which the reflection coefficient of the ground is shown as a function of the angle of incidence, for the whole of the range of ground constants likely to be of importance. Also, the conditions under which the dielectric properties of the ground are otherwise likely to affect the propagation of ultra-short waves have been discussed by McPetrie and Stickland[10] on the basis of an earlier analysis of the problem by Norton[11] in the United States.

(3) IONOSPHERIC WAVE PROPAGATION

Within five years of the setting up of the Radio Research Board by the D.S.I.R., the most important result of its study of wave propagation was the first direct experimental proof of the existence of the Heaviside layer and its effect on the transmission of radio waves. During 1925, Professor (now Sir Edward) Appleton, then a member of the Board, suggested and carried out, with the co-operation of the British Broadcasting Corporation, a series of experiments which provided a crucial test of the existence of such a layer and gave an indication of its height. Ever since this date the Radio Research Board has sponsored continuous investigations of the characteristics of the ionized regions of the atmosphere and of the part they play in determining the propagation of radio waves. These investigations were originally conducted by Appleton and his co-workers at Cambridge University, and later at King's College, London University, while the longer-term work involved was gradually developed by the D.S.I.R. Radio Research Station, Slough, which, since 1933, has formed part of the Radio Division of the National Physical Laboratory.

Many of the results of this work have been described in papers presented to The Institution from time to time, and notably in lectures delivered by Sir Edward Appleton to the Radio Section, the last of which, in 1943, dealt with "Radio Exploration of the Ionosphere."

(3.1) Study of the Characteristics of the Ionosphere

(3.1.1) Measurements made at Normal Incidence.

In the five years prior to 1936, observations of the conditions of the ionosphere, using a normal-incidence sounding technique, had become a well-conducted daily routine, and the results had already revealed certain well-defined long-period variations in ionospheric characteristics. Daily measurements at noon at the Radio Research Station, Slough, had shown a marked increase in the maximum ionization densities of the various layers with increasing solar activity. Furthermore, measurements of the reflection coefficient at normal incidence had also indicated a similar tendency in the ionization density in the lowest part of the ionosphere. The continuation and extension of these measurements during the past ten years have amply confirmed these early conclusions, and at the same time have brought to light new and unexpected complexities in the structure of the upper atmosphere. With the rapid increase in the extent of the application of ionospheric data to radiocommunication problems it is now necessary to predict average ionospheric conditions for weeks or even months ahead, and in our attempt to meet this requirement satisfactorily this large body of basic ionospheric data, accumulated from routine work over a period of fifteen years, has proved invaluable.

(3.1.2) Basis of Forecasting Work at the Radio Research Station, Slough.

The regular variation, diurnally, seasonally and with the sunspot cycle, of the ionization density of normal Region E and Region F_1 has simplified the task of quantitative prediction of the future state of these layers. Many years' measurements at Slough and elsewhere have shown beyond doubt that the ionization density in these two layers is controlled by solar ultraviolet radiation. If we denote the normal-incidence critical frequency by f° and the zenith angle of the sun by χ, then it can be shown theoretically that the quantity $(f^\circ)^4/\cos \chi$ (termed by Appleton and Naismith[13] the "region character figure") should be proportional to the intensity of the ionizing radiation. This region-character figure has formed the basis of long-term prediction at the Radio Research Station for normal Region E and for Region F_1.

When the variations in the ionization density of Region F_2 are considered, a very large degree of irregularity is disclosed, and no completely satisfactory theoretical basis on which to predict the normal-incidence critical frequency of this region, even for short periods ahead, has yet been found. Forecasting for this

region still depends largely on the accuracy with which we can extrapolate from past data. Recently evidence has been obtained of even greater complexity in the world distribution of the ionization density in the F_2-region, than would have been expected from a long sequence of observations at one site. During the war period the number of stations making normal-incidence ionospheric measurements increased from less than ten in 1939 to more than forty at the close of the war, and one of the most striking facts which has come to light with this increase is that the ionic density of Region F_2 is certainly not a simple function of geographical latitude. In a recent communication,[12] Appleton has pointed out that there is a definite asymmetry in the world distribution of the ionization density of this region, with respect both to longitude and latitude, and the variation in the noon ionization density for two stations at the same latitude but at different longitudes is sometimes very large. Thus, two stations at practically the same latitude but at different longitudes may have a difference of 25% in the average noon critical frequency corresponding to a difference of 44% in the ionization density. This new complication in the world picture of the ionization density in the F_2-region has made the forecasting problem even more difficult than hitherto, since we can no longer assume that, for predicting average conditions, local time and longitude are interchangeable. However, although this new fact has complicated the problem, it has also provided evidence of a relationship between the ionization density of the region and magnetic phenomena, in particular with magnetic dip. This correlation with an easily measured magnetic element may, in future, be of assistance in forecasting critical-frequency values for this region.

At this juncture it is convenient to refer to work on another irregular feature of upper-atmospheric ionization, namely the occurrence of abnormal or sporadic E-ionization. In the last few years we have realized to an increasing extent the importance of this layer in long-distance communication work, and in this connection it is relevant to refer to two papers which are representative of work conducted within the programme of the Radio Research Board during the last ten years.

(3.1.3) **Abnormal or Sporadic E-Ionization.**

In 1935, Appleton and Naismith had suggested that ionization occurring near the 100-km level could be classified as "normal" and "abnormal." What was termed the normal ionization of the region, or more briefly "normal Region E," was shown to vary in a regular manner with the solar zenith angle. The abnormal ionization, on the other hand, varied very irregularly, due, presumably, to the variability of the unknown agency responsible for such ionization. Since the appearance of that paper, Appleton and his co-workers have published two further papers dealing with this abnormal ionization. In the first of these,[13] published in 1939, the structure of the abnormal layer was examined, and it was concluded that it generally consisted of thin patches or strata of ionization embedded within the normal E-region. It was also noted that observations of reflections from this layer at two sites only 96 km apart were often uncorrelated, a fact which emphasized strongly the irregular variation of the ionization density of this layer in the horizontal direction. In the second paper,[14] published in 1940, the Slough data for the period 1934–37 were examined for a possible variation in the abnormal E-ionization over the solar cycle, but for these years, during which there was a very marked increase in sunspot activity, no correspondingly large increase in the production of ionization in the abnormal E-region was noted. For forecasting work it would be an important step forward if the source of this ionization could be positively identified, but so far all attempts made to ascribe the occurrence of it to a particular agency have met with considerable difficulties. For example, from the Slough observations it is clear that the incidence of this type of ionized layer is most marked during the daytime and in local summer, and to this extent it exhibits a degree of solar control. On the other hand, the fact that such ionization is very often observed at night shows that some agency not proceeding from the direction of the sun can also give rise to it. The reconciliation of these two experimental facts presents the major difficulty in identifying the real cause of the phenomena. As a result of very recent observations, Appleton and Naismith suggest that all abnormal E-ionization can be attributed to the effects of meteors passing through the upper atmosphere.

(3.1.4) **Absorption Measurements.**

Measurements of the normal-incidence critical frequencies and equivalent heights of the various ionized layers provide us with information on the structure of the upper atmosphere: but for many problems it is desirable to have in addition adequate information on the amplitude of radio waves reflected by the ionosphere. The first quantitative measurements of the reflection coefficient of the ionosphere were probably those made by Appleton and Ratcliffe in 1930,[15] and during the period 1930–36 considerable work was carried out on this subject by the radio research group at Cambridge. Two of the more important conclusions of these workers were, first, that in the daytime considerable absorption occurred in a region in which the refractive index is practically unity and situated below the level of maximum ionization of the normal E-layer, and secondly, that at night it appeared that most of the absorption occurred near the top of the ray trajectory. From these reflection-coefficient measurements valuable quantitative estimates were also obtained of the values of the collisional frequency of electrons with molecules at various levels in the ionosphere.

In the Bakerian lecture to the Royal Society in 1937[16] Appleton applied the theory of layer formation, which had been advanced by S. Chapman in 1931, to deduce the seasonal variation to be expected in ionospheric absorption. It was noted that whereas, for a station in the latitude of Great Britain, the theoretical ratio of summer/winter absorption at noon should be about 6·4:1, the daily observations made at noon during 1935–36 on a frequency of 4 Mc/s indicated that the actual ratio was only 2·6:1. Two possible explanations were offered to account for this large discrepancy between theory and experiment. Either the noon winter values of absorption were spuriously high due to group retardation in Region F_1, or alternatively the ratio of summer/winter absorption was reduced owing to the occurrence of absorption in a low layer in which the collisional frequency is of the order of magnitude of the radio-wave frequency. Later work has tended to support the latter suggestion. In this paper Appleton also showed that the ratio of 2·6:1 deduced from normal-incidence absorption work fitted in remarkably well with measurements made in 1931 by Burrows[17] on the seasonal variation in the intensity of radio signals transmitted across the North Atlantic.

Systematic observations of the ionospheric absorption at normal incidence each day at noon, which began at King's College, London, in 1934, were continued at Cambridge in the period 1936–38, and since that time this same series has continued without interruption at Slough. As a result, an unbroken series of normal-incidence measurements of ionospheric absorption on at least one frequency is available from 1934 to the present time. These long-term observations have shown that there is a pronounced change in ionospheric absorption over the solar cycle; for example, the absorption on a frequency of 4 Mc/s at normal incidence in the summer of 1937 is some four times as great as that observed at the period of minimum sunspot activity.

The application of normal-incidence ionospheric absorption measurements to calculate and predict the field strength to be expected in radiocommunication problems is not so advanced as is, say, the calculation of the maximum penetration frequency at oblique incidence. Apart from the complexity of the actual problem of converting from the normal-incidence to the oblique case, there is a complete lack of measurements of ionospheric absorption in other parts of the world. Theoretical work has been going on for some time, and it is hoped that, before long, satisfactory methods will be devised for applying normal-incidence absorption results to communication problems in the ready manner in which critical frequency data have been used for many years past. Meanwhile, the bulletin of measured ionospheric characteristics issued by the Department of Scientific and Industrial Research to interested users has, since January 1942, contained values of ionospheric absorption measured at noon at Slough. In 1937, Ross[18] used the available knowledge of the effective reflection-coefficient of the ionosphere to compute the relative intensities of the ground and ionosphere waves for various frequencies and over a range of distances useful for communication and direction-finding.

(3.2) Development of Equipment for recording Characteristics of the Ionosphere

In 1936 the observations of equivalent height of reflection as a function of frequency were made at the Radio Research Station, Slough, partly with an automatic equipment of very limited frequency range, and partly by the so-called manual or semi-automatic technique in which the frequency of the pulse sender was slowly varied and the tuning of the receiver continually adjusted by an operator. The automatic equipment depended on a mechanical linkage between the main tuning capacitors of the sender and receiver, a method which was partly satisfactory for low frequencies but which became increasingly troublesome at higher frequencies. Hence only a limited frequency range from about 2 to 5 Mc/s was attempted with this early automatic equipment. Since 1936, development of apparatus for recording height of reflection as a function of frequency has proceeded along two lines.

In April 1936 Naismith[19] described the basic principle of a method whereby synchronism between the sender and receiver could be achieved by an electrical linkage. In this equipment the frequency of a conventional amplitude-modulated pulse transmitter is slowly varied whilst valve-operated relays continuously adjust the tuning capacitor of the receiver so as to maintain the receiver tuned to the frequency of the transmitter. Since 1936, this technique has been developed to a high degree of reliability, and for the last three years a completely automatic ionospheric recorder developed by Naismith and Bailey, operating in a period of about five minutes over the frequency range 0·5–16 Mc/s, has been in routine use at the Radio Research Station, Slough.

The fundamental principle of the second line of development was first described in 1935.[20] In this method, the frequency of a continuous-wave sender is varied rapidly so that the whole frequency band is covered 25 times a second. As the sender sweeps through the frequency to which the receiver is tuned, pulses of energy are received, the shape of the envelope of these pulses being determined by the frequency-response curve and bandwidth of the receiver. This method has the advantage that there are practically no receiver/transmitter ganging troubles to be overcome, but it has the limitation that there are technical difficulties in obtaining a sufficiently short pulse of energy at frequencies much below about 2 Mc/s. In the original model, developed by Thomas and Chalmers, the receiver was tuned through the whole frequency band (2–16 Mc/s) in 12 sec, but in the later models it was found desirable to reduce this rate of sweep to about one per minute. During the war period a number of equipments of this type were manufactured by a commercial firm and they are now in regular use at many observatories throughout the world. During the development of these equipments, some theoretical and experimental work was carried out at the National Physical Laboratory with the object of designing the types of transmitting and receiving aerials most suitable for use with multi-frequency automatic ionospheric equipment.

(3.3) Oblique Incidence Work

From the standpoint of the communications engineer, the real value of normal-incidence data is measured by the extent to which it can help in selecting suitable frequencies for communication between any two given stations. The need thus arises for studying the manner in which normal-incidence data can be applied to the solution of oblique-incidence problems. An important practical quantity is the highest frequency at which waves can be transmitted by the ionosphere from one station to another, and during the past six to eight years satisfactory methods of converting normal-incidence critical frequency and equivalent height measurements into oblique-incidence maximum usable frequencies (M.U.F.'s) have been developed. Within the programme of the Radio Research Board, Appleton and Beynon have developed a method of calculating this limiting frequency on the assumption that the vertical distribution of electron density in the reflecting region is of parabolic form. This method has formed the basis of all calculations of M.U.F.'s at the Radio Research Station since 1939, and details of it may be found in two published papers.[21]

With the object of checking this theoretical work, oblique-incidence pulse-transmission experiments were begun in January 1941 between Slough and a station installed at Burghead, Scotland, with the co-operation and assistance of the British Broadcasting Corporation. The distance between the sending and receiving stations is about 700 km and represents about the longest practicable path which can be obtained conveniently within this country. It has been found from a large number of measurements that the discrepancy between theory and experiment for reflections from Region F_2 is of no practical significance for this distance of transmission. Attempts to check the calculations for signals reflected from normal Region E were unsuccessful because it was found that, at oblique incidence, reflections from this region were often obscured by stronger signals reflected from the abnormal or sporadic E-layer. The upper limiting frequency for reflections from this layer showed no close relationship with the simultaneous normal incidence observations made at Slough and Burghead, because of the irregular horizontal distribution of sporadic E-ionization. It is now known that this further confirmatory evidence of the irregular spatial distribution of this type of ionized layer is of considerable practical importance in the prediction of M.U.F.'s. It is unfortunate that the war has prevented the extension of measurements of this kind to greater distances, but signals from short-wave broadcasting stations on the continent of Europe have been used for checking the accuracy of theoretical analysis. In these experiments the M.U.F. has been observed from the rapid variations in the ionized layer occurring at sunrise and sunset periods, and the high accuracy of the controlled pulse experiments could not be achieved. Nevertheless it has been shown that up to distances of 2 500 km the calculated values of the M.U.F. were accurate to within about $\pm$ 3% for given ionospheric conditions. In the course of these check experiments, which are described by Beynon in a recent publication,[22] some extremely regular fluctuations in the signal amplitude were observed near the edge of the skipped zone.

These rhythmic variations in field strength could be explained in terms of interference between magneto-ionic components or between oblique rays of high and low elevation as the signal frequency approached the M.U.F. The possibility of using information of this kind as a practical warning of the approach to penetration may merit attention.

The experiments just mentioned indicated that no serious divergence between calculated and observed values of the M.U.F. would be expected, provided the controlling ionospheric conditions were accurately known. During the past few years, however, a body of evidence has been accumulated indicating that satisfactory radio communication could often be maintained for quite long periods on frequencies considerably in excess of the M.U.F.'s predicted for the three regular reflecting regions (normal E, F_1 and F_2). Unfortunately, much of the early evidence concerning this anomaly was of a rather qualitative character, and in many cases referred to transmission paths for which no normal-incidence ionospheric data were available. Some particularly useful quantitative information on this point has, however, been supplied by the B.B.C. Engineering Division. These data indicate conclusively that signals from the Daventry short-wave station could be received regularly in Gibraltar and Algiers on frequencies which were from one to six megacycles per second in excess of the monthly mean values predicted from normal-incidence ionospheric data. A careful study of this evidence led to the conclusion that the large majority of observations of this kind over distances up to about 2 000 km were due to reflections from sporadic E-ionization. Our normal-incidence observations at stations 50–100 km apart had already emphasized the irregular spatial and temporal variations of sporadic E-ionization, and it was therefore not surprising that predictions of the M.U.F. based on observations at just one site should often not represent the practical upper limiting frequency for oblique transmission.

Advantage was taken of the eclipses of the sun of 1936 and 1945 to carry out observations at both vertical and oblique incidence during the rapid cutting off and restoration of the sun's illumination of the ionosphere which occurs on such occasions.[23]

(3.4) Theoretical Developments

Turning to theoretical work on the ionosphere, Appleton[16] in 1937 considered a number of important points connected with the application of Chapman's theory of layer formation in the upper atmosphere. Expressions were deduced for the variation of ionization density and ionospheric absorption with solar angle, and for the direct conductivity of a solar-controlled ionized region. The processes of electron production and decay in the ionosphere were examined in some detail, and it was shown how the actual height of reflection of radio waves could be deduced from equivalent height measurements.

In a discussion of reflections by sporadic E-ionization Appleton, Naismith and Ingram[24] examined the formulae used in the application of the critical frequency method of measuring upper-atmospheric ionization and showed that these formulae are valid when the thickness of the ionized layer is large compared with the wavelength of the radio waves used. The effect of a thin layer, such as the sporadic E-layer, embedded within a thick layer was also considered, and expressions for the equivalent height of this compound ionospheric structure were given in a second paper on this subject.

One of the problems connected with the ionosphere which has aroused much controversy is the question of whether the Lorentz or Sellmeyer dispersion formula should apply to the case of refraction by an ionized medium. The question is one of more than academic interest, for if the Lorentz formula applies, then our estimates of the true ionic density will need to be increased by about 50%. In the past ten years there have been many publications supporting each side of this issue. In two important theoretical papers published in 1934 and 1943 Darwin[25] concludes that the Sellmeyer formula should apply to the ionosphere. On the experimental side, the position may be summarized in these terms. From observations near the gyro-frequency, Booker and Berkner favoured the Lorentz formula, whereas from other similar experiments, Martyn and Munro supported the Sellmeyer case. The experimental and theoretical work of Ratcliffe suggested that a conclusive experimental test might not be possible, whilst similar work by Newbern Smith concluded in favour of the Sellmeyer formula. In a paper circulated to the Radio Research Board in 1943 and now published, Beynon[26] extended the theoretical work of Ratcliffe and showed it to be consistent with that of Newbern Smith. Applying this theoretical work to the results of some oblique-incidence measurements of the M.U.F., it was concluded that a satisfactory explanation was only possible in terms of the Sellmeyer theory.

In 1939, Appleton and Weekes[27] showed the existence of a lunar tide effect in the height of Region E of the ionosphere. The tide was found to be semi-diurnal, with an amplitude variation of about $\pm$ 1 km. If these results are interpreted according to the simple theory of the formation of the ionized regions, they indicate a relative air-pressure oscillation several thousand times the measured relative pressure oscillation at ground level.

(3.5) Long-Wave Propagation

Investigation of the propagation of very long radio waves through the ionosphere has been carried out with the support of the Department of Scientific and Industrial Research by workers at the Cavendish Laboratory, Cambridge, and reference may be made to some of the results contained in two papers published in the past ten years.

In 1936, Best, Ratcliffe and Wilkes[28] gave an account of experiments in which the amplitude, height of reflection, and polarization of waves of frequency 16 kc/s reflected from the ionosphere were measured for angles of incidence of about 30°. In one set of experiments, observations were made at a number of points on the ground between 65 and 145 km from the sender, and the equivalent height of reflection and the reflection coefficient were deduced from the interference pattern resulting from the simultaneous reception of ground and ionospheric waves. These results indicated a marked diurnal and seasonal change in both the level of reflection and the reflection coefficient. On a September day the equivalent height was about 74 km and the reflection coefficient about 0·25, whereas on a November night the corresponding quantities were about 90 km and 0·5 respectively. In the second set of experiments the polarization of the received signal from the ionosphere was found to be approximately circularly polarized with a left-handed sense. It was also concluded that these long waves are reflected without first traversing an absorbing region at all significant compared with that operative in the case of medium and short waves.

In a paper[29] published in 1939, Budden, Ratcliffe and Wilkes gave the results of further measurements at 16 kc/s, the distance between sender and receiver in this case extending to 380 km. The results concerning the level of reflection are here not completely unambiguous, but the authors conclude that over sender/receiver distances of 100–400 km, it is most likely that reflection takes place at a constant level of about 67 km. It was noted that the ionosphere signals on this frequency of 16 kc/s were subject to two kinds of disturbance. The first was sudden and short-lived, and appeared to be related to the fade-out of short waves; the second type of disturbance appeared to be associated with magnetic storms and aurorae, and the effect of these was often noticeable over periods up to 10 or 12 days.

(3.6) Direction of Arrival

During the past ten years the steady improvement in the accuracy of radio direction-finding has resulted in the accumulation of a very large amount of accurate data on the deviations in the horizontal plane, of the direction of arrival of ionospheric waves. In general, it is found that the magnitude of the lateral deviation increases as the angle of incidence of the ray decreases. Thus, in the frequency band 3–30 Mc/s, for a distance of 100 km, the statistical value of the lateral deviation is found to be about 7°; when the distance is increased to 250 km, the value falls to about 2·5°, and at very great distances it may be 1° or less. Long-term measurements on bearing fluctuations of signals from distant stations show that there are slow variations in the direction of arrival of the incoming signal which are superposed on the moment-to-moment fluctuations. Up to the present time, satisfactory correlation between observed ionospheric variations and these deviations in the angle of arrival of the ionospheric ray has not been established, but there have been occasions, particularly at sunrise and sunset, when we have observed systematic changes in bearing angle which could be interpreted in terms of the known ionospheric conditions. Thus a number of tests made at the National Physical Laboratory during 1941 on pulse signals from transmitters located at distances of 90 and 250 km showed evidence of a sunrise effect during which the incoming radiation tended to arrive from the sunrise zone in the ionosphere and well away from the true bearing. In some cases, too, a definite correlation between fluctuations of the apparent height of reflection and bearing changes was observed. More recent experiments of the same kind have shown that large deviations from the true direction due to horizontal gradients of ionization in the ionosphere occur only if both the density of ionization is changing rapidly and the frequency in use is near the critical value for the path concerned.

No quantitative measurements of the vertical angle of arrival of the ionospheric wave have been made by the Radio Research Board since the work of Wilkins[30] in 1934, but it is planned to resume work on this problem in the near future.

(4) TROPOSPHERIC WAVE PROPAGATION

For wavelengths greater than about 10 m, propagation is influenced to a negligible extent by variations in the conditions of the troposphere, which is that part of the atmosphere extending up to a height of about 10 km. The effect of atmospheric refraction on such waves may be taken into account quite simply as already indicated in Section 2.1, i.e. by reducing the problem to one of diffraction around an "equivalent" earth having a radius somewhat greater than the geometrical value. This smoothing-out of refraction effects is possible because local abnormal variations of the refractive index of the atmosphere almost invariably occur over regions small compared with the wavelength in question. As the wavelength is progressively reduced below 10 m, however, this is no longer the case, and the detailed refractive-index structure of the atmosphere becomes of increasing importance.

(4.1) Dependence of Very-Short-Wave Propagation on Meteorological Conditions

It is well known that in a normal well-mixed atmosphere the refractive index decreases steadily with height. This decrease is due to two factors: first, the decrease of density with height, though this is also modified by the normal decrease of temperature with height; and secondly, the lapse (i.e. decrease) of water-vapour density with height. This second effect is of greater importance for radio than for light waves, because the permanent electric polarity of the water molecule causes water vapour to make a greater contribution to the total refractive index of the atmosphere for radio waves than for light.

The decrease of refractive index with height leads to a downward bending of the path of a radio wave. It frequently happens that in the lowest levels of the troposphere, departures occur from the normal refractive-index lapse-rate, leading to increased bending of rays, or, less frequently, to decreased bending. These phenomena have come to be known as super-refraction and sub-refraction respectively. As mentioned above, such effects are pronounced only with very short waves, when the wavelength is small compared with the range in height of the region through which the variation of refractive index is abnormal. A detailed analysis of these conditions has been made by Stickland,[31] who has examined much meteorological data relating to temperature and humidity in various parts of the world, but particularly in the British Isles. This work has served to determine the variation of refractive index with height, and thus the amount of bending suffered by very short radio waves.

If m is the ratio of the radius of curvature of the ray to that of the earth, then the propagation may be regarded as rectilinear relative to an earth of effective radius $m/(m-1)$ times its geometrical value. Stickland's analysis of the meteorological data shows that there is a general increase of m with height above the ground, which is approximately linear, and may be expressed in the form

$$m = 2{\cdot}5 + h \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where h is the height in kilometres. This relation may be used in general for the estimation of bending to be expected in the region of the British Isles at all times of the year. Fig. 4 shows

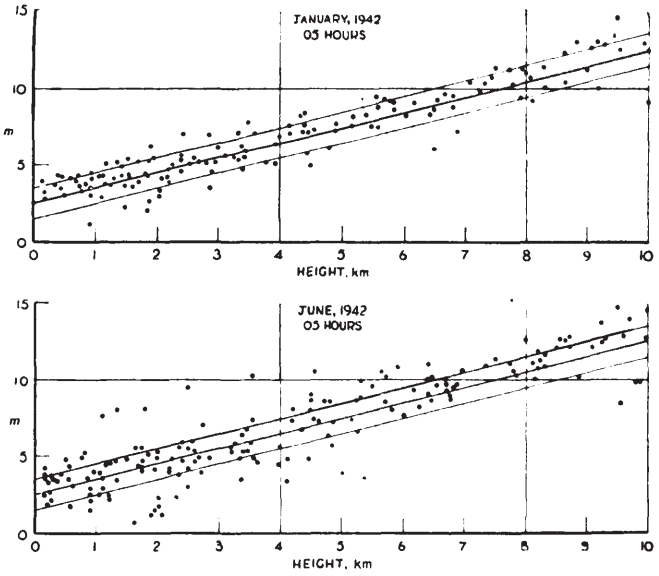

Fig. 4.—Variation of m with height: Penzance.

values of m as a function of height calculated from meteorological data obtained from radiosonde ascents at Penzance in Cornwall during January and June, 1942. The middle line through the points is the one derived from equation (3); the two other lines give values of m that differ from this by $\pm$ 1 respectively. There is rather a greater spread of the points in June than in January, but above the lowest few kilometres equation (3) may be regarded as a satisfactory approximation to the actual state of affairs. It is not surprising that the greatest variability in conditions exists nearest to the ground in summer time, for it is then, for example, that the earth's surface suffers its greatest variation in temperature over relatively short periods of time,

and this has its effect on the state of the air immediately in contact with the ground.

A more convenient parameter than m for use in the analysis of propagation phenomena in the lowest levels of the atmosphere is the "modified refractive index," M: this is defined as

$$M = \left(n - 1 + \frac{h}{R}\right)10^6 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where n is the refractive index at height h, and R is the radius of the earth. It may readily be shown that

$$\frac{dM}{dh} = \left(\frac{m - 1}{m}\frac{1}{R}\right)10^6 \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Thus the gradient of the (M, h) curve changes from positive to negative as m passes through unity, that is as the radius of curvature of the ray passes from being greater than to less than that of the earth: in the latter case the ray will be bent back towards the earth.

Rays may also be returned to the earth by reflection at grazing incidence at discontinuities of refractive index such as are sometimes produced by temperature inversions at heights of the order of a few kilometres. Such inversions are capable of reflecting radiation on wavelengths up to several metres.

It will be seen, therefore, that meteorological variations may cause considerable fading in the reception of radiation on a wavelength of less than 10 m at stations beyond the normal optical range of the transmitter, and the shorter the wavelength the more pronounced will be the effects obtained. Reflections from high-level inversions are generally more important for metre waves at extreme ranges, whereas the refraction effect, leading in some cases to "guided-wave" propagation,[32] is usually of greatest significance in the centimetre-wave region.

As the wavelength decreases below 10 cm there are further aspects of the meteorological conditions which must be taken into account in considering the propagation of such radiation. Rain, particularly when it is heavy and composed of large drops, and to a lesser extent clouds, fog, hail and snow, are all capable of absorbing and scattering centimetre waves to a degree which, in general, increases with decreasing wavelength. There is also absorption by oxygen and water vapour which is of importance in some parts of the spectrum. Absorption by water vapour is appreciable at wavelengths less than about 2 cm, and at wavelengths less than 2 mm the atmosphere becomes virtually opaque for nearly all radiation lying within the region of the water-vapour infra-red absorption spectrum. The absorption is likely to be considerable under normal atmospheric conditions, owing to the broadening of the absorption bands by molecular collisions.

There is very strong absorption by oxygen in the immediate neighbourhood of the wavelength of 5 mm. A less strong, and even sharper, resonance absorption in oxygen occurs at about 2·5-mm wavelength.

(4.2) Fading Phenomena and Anomalous Refraction

Smith-Rose and Stickland[33] have analysed field-strength measurements obtained during the years 1937–39 over the Post Office radiotelephone link between Guernsey and Chaldon, England, on wavelengths of 5 and 8 m. The path between the terminal points is almost entirely over sea and about 135 km (85 miles) in length, of which some 58 km (36 miles) is outside the geometrical optical range. Considerable fading was observed, amounting in extreme cases to 60–80 db. The field-strength records showed marked correlation between periods of negligible fading and the existence of low atmospheric-pressure conditions, including lack of appreciable temperature inversion. In a general way, at least, the range of variation of the received signal strength may be accounted for by variations in moisture content, and so in refractive index, of the lower atmosphere along the direct-ray path. It is, however, not possible to rule out the likelihood of the existence of indirect paths, such as those involving reflection at refractive-index discontinuities formed by inversions at heights of the order of a few thousand feet. Indeed, in the light of subsequent experience, such indirect rays must be regarded as probable, and these, interfering with the direct ray, would also lead to considerable fading. The results of this investigation confirm, and in some respects extend, the earlier observations of other workers, notably those in America. It is generally agreed that whereas a diurnal variation in fading occurs on over-land paths it occurs extremely rarely, if at all, on over-sea paths: this is in keeping with the known variation of meteorological conditions in the two cases.

With the extension of radio-frequency techniques and application to shorter and shorter wavelengths during the war years of 1939–45, it became essential to study intensively the effect of meteorological conditions on the transmission of radio waves on wavelengths down to a few centimetres. For this purpose a comprehensive and co-operative investigation was carried out in which staffs of the Admiralty, Ministries of Supply and Aircraft Production, the Meteorological Office and the National Physical Laboratory and also the Research Laboratories of the General Electrical Company have each played an important part. The general scheme of this investigation, which involved transmissions on wavelengths of 9 and 3 cm over various sea paths in the Irish Sea, has recently been described by Megaw,[34] in a paper read before the Radiolocation Convention. The National Physical Laboratory was responsible for the detailed analysis of the data obtained over the radio links across Cardigan Bay, and in the later stages of the experiments all the stations in operation were provided with monitoring equipment developed at the N.P.L. This equipment took the form of a field-strength meter and standard radiator for centimetre waves, and has been described in a Radiolocation Convention supporting paper,[35]

For a period of some three years up to 1945 a study was also made of the propagation of 9-cm waves over an entirely land path between the Admiralty Signal Establishment, Haslemere, Surrey, and the Research Laboratories of the General Electric Company at Wembley. The results of a study made at the N.P.L. of the observations obtained in these over-sea and over-land paths have been described in recent papers.[36, 37]

From all this work it has been established that the propagation of centimetre waves over sea or land is directly associated with the meteorological conditions in the part of the atmosphere through which the waves travel. With the help of meteorological soundings made by aircraft flying over the Cardigan Bay paths between the sending and receiving stations, it has been possible, when reasonably uniform conditions existed over the whole path, to show that the general level of the received radio signal was directly dependent upon the average gradient of the atmospheric refractive index over the path, in a manner agreeing with existing theoretical work. The extent of this agreement is illustrated in Fig. 5. It is considered that the overall accuracies of both the meteorological observations and the absolute radio field intensities were such as to justify the introduction of the arbitrary range of ± 10 db shown in Fig. 5 as the overall margin of probable error. Some 70% of the results plotted will be seen to fall within the limits so defined.

The four transmission paths across Cardigan Bay were nearly equal in length, and ranged from one having a clear line of sight between the transmitter and the receiver to one in which the transmission distance was about 2·5 times the optical range. The other two paths were also non-optical, but to a lesser degree. The observations showed quite clearly that, notwithstanding the

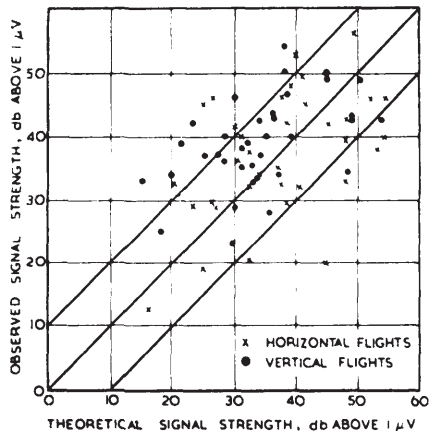
OBSERVED SIGNAL STRENGTH, db ABOVE 1 μV
THEORETICAL SIGNAL STRENGTH, db ABOVE 1 μV
x HORIZONTAL FLIGHTS
● VERTICAL FLIGHTS

Fig. 5.—Radio wave transmission across Cardigan Bay (Link BC) during April–May, 1945, on frequency of 3 260 Mc/s (wavelength 9·2 cm).

extreme variations in atmospheric refraction, the higher the terminal points the more reliable was the link for radiocommunication purposes on both the wavelengths (3 and 9 cm) used.

(4.3) Laboratory Study of the Properties of Atmospheric Constituents at Very High Radio Frequencies

In 1941 an investigation was begun at the National Physical Laboratory with the object of measuring the dielectric properties of water vapour at centimetre wavelengths to see whether atmospheric water vapour was likely to absorb such radiation to an appreciable extent. The first observations were made with a wavelength of 9 cm, and they were later extended to wavelengths of 3·2 and 1·6 cm. It was considered at the time that the existing experimental facilities and techniques were insufficient to measure the small difference in absorption expected in a laboratory comparison of dry air with air containing the usually occurring amounts of water vapour. The effect was therefore magnified some hundred times by making observations on dry steam. The basis of the measurements was the comparison of the resonant frequencies and Q-factors of a hollow metal resonator when filled alternately with dry air and with steam.

Some difficulties are encountered in deducing the effects of atmospheric water vapour on radio-wave propagation from a knowledge of the electrical properties of steam: these are due to the differing widths of the absorption lines in the vapour in the two cases. This question is discussed in detail in a recent paper by Saxton,[38] where it is shown, however, that the difficulties can in some measure be surmounted. The measurements indicated that, under typical conditions of humidity in temperate zones (say 7·5 g/m^3 of water vapour at 20° C), the attenuation of 9-cm and 3-cm waves would be not greater than 4.10^{-3} and 4.10^{-2} db/km respectively, and the attenuation to be expected at 1·6-cm wavelength would be about 8.10^{-2} db/km. These values have subsequently been shown to be of the right order of magnitude by experience in the operation of radar equipment in this country, and by other work in America.

Although a rigorous theory exists for determining the scattering and absorption of electromagnetic waves by dielectric spheres, e.g. raindrops, it was found that our knowledge was deficient in two respects when the problem of the effect of rain, fog, etc., on centimetre-wave propagation was considered. In the first place, statistical information relating to drop-size distribution in such phenomena was far too meagre; steps have been taken by the Meteorological Office to remedy this limitation. Secondly, the dielectric properties of water at such wavelengths were not known with sufficient accuracy. This latter problem has therefore been investigated at the National Physical Laboratory during the past two years, and the results have been described recently by Saxton and Lane.[39]

In the range of wavelengths from 10 cm downwards, which is of great interest in many radio and radar applications, the dielectric properties of water vary in a most marked manner with wavelength; this is because water exhibits anomalous dispersion in this wavelength region owing to the permanent electric polarity of its molecules: for this reason, too, the dielectric properties at any given wavelength in the centimetre band vary markedly with temperature. Figs. 6(*a*) and 6(*b*), for

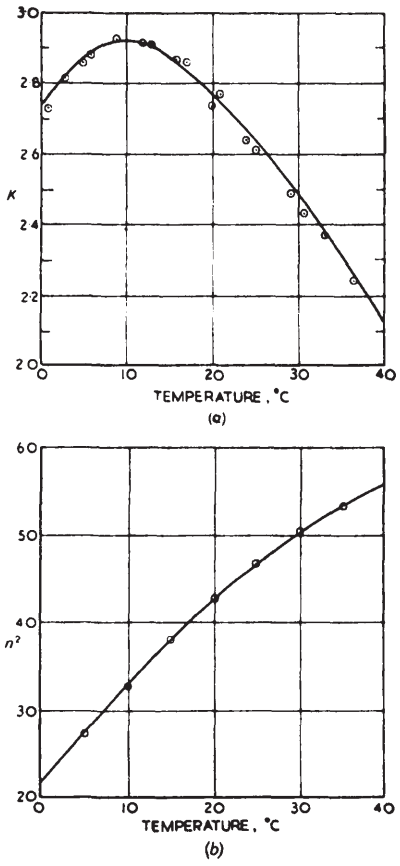

Fig. 6.—(*a*) Variation of absorption coefficient (κ) of water with temperature.
(*b*) Variation of (refractive index)^2 of water with temperature.
Wavelength, 1·24 cm.

example, show the variation of the refractive index and absorption coefficient of water between 0° C and 40° C for the wavelength of 1·24 cm. Experiments were actually made over this temperature range with the two wavelengths of 1·24 cm and 1·58 cm. An examination of the theory of dipolar dispersion[40] has led to a satisfactory extrapolation of the results to cover the wavelength range 2 mm–10 cm, and Fig. 7 shows the variation of the refractive index and absorption coefficient of water at 20° C over this wavelength range. The agreement between the theoretical extrapolation and the best previously existing experimental data at wavelengths between 4 and 10 cm can be seen to be good.

Since the equivalent conductivity of water due to dipolar absorption at wavelengths of the order of 1 or 2 cm and less is so much greater than the ionic conductivity in sea water, the

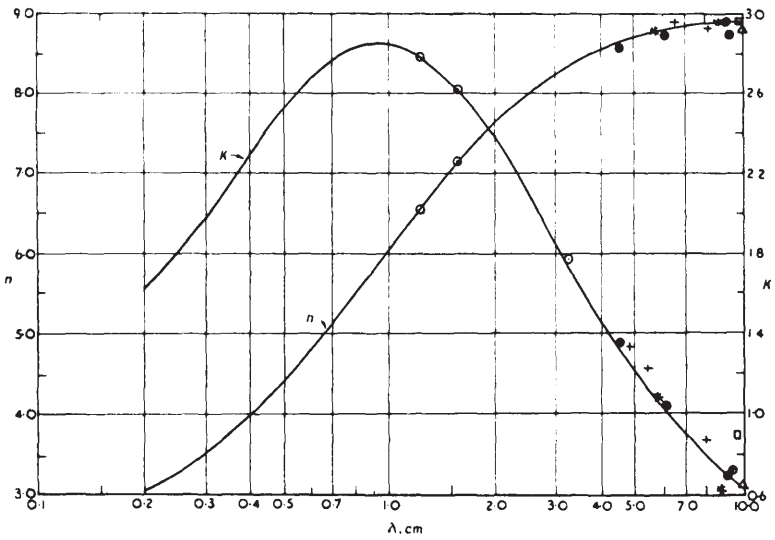

Fig. 7.—Theoretical curves showing variation of absorption coefficient (κ) and refractive index (n) of water with wavelength.
Temperature, 20° C.

dielectric properties of the latter in this waveband do not differ greatly from those of pure water:[41] differences between the two begin to be apparent for wavelengths greater than about 4 cm.

The results of these investigations on the dielectric properties of water have been used by Ryde[42] in a comprehensive treatment of the scattering and absorption of centimetre and millimetre waves by rain and fog.

This brief review shows that, while we now understand something of the manner in which the transmission of very short radio waves is influenced by the actual conditions of the atmosphere through which they travel, there is still a great deal to be learned before we shall be able to exploit to the full the possibilities of these waves for various applications connected with communication, broadcasting, radar and navigational aids. At the present time, satisfactory progress in some of the investigations is dependent upon the advance of knowledge of the actual meteorological conditions of the atmosphere, and as these are very variable in different parts of the world, it is clearly desirable that the propagation of very short waves must also be studied on a world-wide basis.

(5) ATMOSPHERIC AND EXTRATERRESTRIAL NOISE

It has long been well known that the overall efficiency of any radio communication or radar equipment depends not only upon the strength of the wanted signal created at the receiver by the sender, but also upon the ratio of this wanted signal to any unwanted signals, including extraneous noise. From the earliest days of radio applications the occurrence of atmospherics has constituted an obstacle to successful communication. It was realized almost from the beginning that atmospherics were related to thunderstorms and natural electric discharges, and later it became clear that the effect, at a distant point, of the radiations initiated by such discharges depends primarily on the frequency under consideration and the propagation conditions appropriate thereto. More recently it has become clear that receivers operating in the very-short-wave end of the radio spectrum are susceptible to "noise" radiations from the sun and other celestial bodies, but here again the nature and amount of such radiation reaching a receiver located near the earth's surface depend upon the conditions in the portions of the ionosphere through which these radio waves of natural origin must be transmitted.

(5.1) Atmospherics, their Nature and Origin

The general investigation of atmospherics has formed an important part of the programme of the Radio Research Board since 1922, when experiments were begun with the object of finding out the nature and origin of atmospherics. The earliest observations, conducted by Appleton, Watson-Watt and Herd, sufficed to reveal the complexity of the subject. An examination of the signal currents induced in a receiving aerial by a distant discharge showed that a large variety of waveforms was possible, and that both the intensity and waveform varied between very wide limits with the distance over which the radiations had travelled. A special directional receiver using a pen recorder was developed[43] to facilitate the study of the direction of arrival of the main streams of atmospherics, while the visual-indicating direction-finder with cathode-ray-tube presentation as we know it to-day owes its origin to the development, by Watson-Watt and Herd, of an instrument[44] giving direct and instantaneous readings of the direction of arrival of atmospherics. By 1936, a large amount of observational material had been accumulated at two stations in this country and at others overseas. A study of this material was combined with a statistical analysis of synchronized records taken at Slough in south-east England and at Leuchars in Scotland over a period of several years. The results of this work showed that most of the atmospherics received on long waves in this country arrive from the west or south-west, but during summer afternoons sources of wide area to the east and south-east are also productive, as well as smaller local storm centres. The main disturbed azimuths were closely related to the directions of the great tropical thunderstorm centres, but the intensity of disturbance from each was dependent upon the conditions in the ionosphere prevailing over the path to the receiver at the time the storm region was productive of radiations.

Concurrently with the above work, Appleton and Chapman[45] had been studying the evolution of the waveform of an atmospheric by observations at various distances on the rapid changes in the earth's electric field, associated with relatively nearby lightning flashes.

A paper published later by Watson-Watt, Herd and Lutkin[46] described the results of a detailed study of the photographic records of the waveforms of the currents induced by atmospherics in an aperiodic aerial system, and it was shown that these were generally of a composite type with two main frequency groups in the region of 500 c/s and 10 kc/s. A feature observed in this and in the earlier work was the existence in many cases of a precursor preceding the main groups by a few milliseconds and consisting of a small number of oscillations of a somewhat higher frequency but of much less intensity than the main group.

With the aid of an improved drum camera[47] giving a much more open time scale than those previously used, special series of observations were made by Lutkin[48] on atmospherics originating near the receiver, with the object of correlating the study of waveform with the actual lightning discharges. Three main types of waveform were distinguished, in each of which there was a progressive change of pattern with distance, and it appeared that each type was associated with a particular form of lightning discharge.

(5.2) Atmospherics and the Location of Meteorological Storm Centres

During the few years immediately preceding the outbreak of war in 1939, these investigations on atmospherics had to give way to the early development of radiolocation in this country. Many of the staff previously engaged on this work were diverted

to the inauguration and development of the new technique in which they were able to exploit the experience and equipment which had been developed for dealing with impulsive radio-frequency radiations and their visual display on cathode-ray tubes. It was at a very early stage in the war, however, that the Department of Scientific and Industrial Research was requested by the Director of the Meteorological Office to assist in the location of thunderstorm areas by the use of cathode-ray direction-finding apparatus of a type suitable for the reception of atmospherics. Accordingly the equipment previously developed and used for research purposes was brought into regular operational use in this country and proved very successful for giving advance information of the approach of thunderstorms to barrage-balloon areas, and so enabling appropriate action to be taken to minimize the destruction of balloons by lightning discharges. This storm-locating network of d.f. stations has since been used as a general ancillary observing instrument for providing information for the meteorological forecasting service. By the use of these instruments, storm centres can be located successfully and their movements followed over a radius up to some 1 500 km, and the information so obtained forms a very useful supplement to that provided by the normal meteorological observing network. To assist in this work the cathode-ray direction-finding equipments used have recently been improved on the lines described in a recent paper by Adcock and Clarke,[49] and as mentioned therein it is proposed to resume the general study of the nature and origin of atmospherics as soon as practicable.

(5.3) Survey of Literature on Radio Noise

In 1943, it became evident that progress in many radio-communication problems was being retarded by a lack of adequate knowledge of the general level of atmospheric noise at various times and in all parts of the world. This was particularly evident in the high-frequency band between about 1 and 30 Mc/s. While, as has been described elsewhere, the study of the ionosphere and of the mode of radio wave propagation through it had advanced very rapidly during the early years of the war to such an extent that it had become possible to make predictions of the general conditions affecting the reception of signals transmitted between two points, existing knowledge on the corresponding conditions for noise reception was very meagre. As a first step towards improving this position the Department of Scientific and Industrial Research arranged for the preparation in 1944 of a survey of the state of knowledge on the whole subject of radio noise, and this survey by Thomas and Burgess is shortly to be published[50] as a Special Radio Research Report by H.M. Stationery Office. A critical examination was made of some 180 published papers on the subject, and, in addition, the opportunity was taken of examining practical communication data and measurements made available by certain Government and commercial organizations operating radio services in this country. The scope of the work has been limited to radio frequencies mainly between 1 and 30 Mc/s (wavelengths 10–300 m), because most of the medium- and long-distance communication and broadcasting is conducted within this range. While this survey is mainly concerned with atmospheric noise, it also deals to some extent with the fluctuation noise generated within the aerial and circuits and valves in the receiver, and with the so-called "man-made" noise produced by such agencies as electrical machinery and motor-car ignition systems. An important section of the report also deals with extraterrestrial noise which originates outside the earth and its atmosphere and which, as we know from recent experiments,[51] comprises streams of radio waves from the sun and from large groups of stars such as the Milky Way. This review of the present state of knowledge should form a good foundation upon which to take up once more the general study of radio noise and its effect in radar and radio-communication techniques.

(5.4) Measurement of Atmospheric Noise Level

At an early stage in the preparation of the survey referred to above, it became clear that our detailed knowledge of the subject of radio noise was very incomplete, and that there was a very wide field open for further investigation. In particular, it was considered that by far the most urgent requirement was to obtain a more precise knowledge of the minimum signal field necessary to maintain the various communication services. With this end in view, it was decided in 1944 to develop a simple and standardized type of noise-measuring equipment which, in co-operation with the appropriate radio organizations in the United States and Australia, could be set up and used at various Service and commercial operating stations throughout the world to study the magnitude of the prevailing atmospheric noise on frequencies between 2·5 and 20 Mc/s. The equipment comprises a vertical aerial connected through a fixed length of cable and suitable matching networks to a commercial receiver, which is also connected to a signal generator continuously keyed with morse characters from a tape-operated unit. The method of measurement consists in determining the value of the output from the signal generator necessary to give, in the opinion of the operator, a 95% intelligibility of the morse signals as heard in his telephones, against the background of atmospheric noise being picked up on the aerial. The readings are expressed as an equivalent field-strength at the aerial, and measurements can normally be repeated to within 2 db, even by relatively unskilled observers. Measurements of noise level have been made at fourteen stations throughout the world for periods of between 6 and 18 months. Observations are taken every hour throughout the day and night, except at one or two stations where shortage of staff render such a complete programme impracticable.

A detailed analysis of the data being received is in progress, and only a few of the early and tentative conclusions so far reached can be quoted here. In the first place, the noise field-strengths observed show a diurnal variation of consistent form at all stations, maximum strengths occurring during the night, with lower and steadier values during the day. The difference between day and night values is small at some stations, but at others it amounts to some 20 db. Secondly, the presence of a definite seasonal variation at any station appears to be doubtful, and is in any case small compared with the variations which take place from day to day. Furthermore, the general noise level decreases with increase of frequency at all stations, but no definite law connecting the noise field with frequency can yet be deduced. In any case, it appears that the prevailing noise field-strength at any point is determined more by the prevailing conditions of wave propagation through the ionosphere than by the occurrence of atmospheric storms near the receiving stations: indeed it seems that local storms which produce a sufficient frequency of atmospherics to dominate the general noise level for any considerable time are not common. The effects produced by distant storms are very varied, and if the ionospheric conditions are suitable an appreciable increase of noise level can occur at the higher frequencies (up to 20 Mc/s) with no corresponding increase at the lowest frequency (2·5 Mc/s) so far investigated.

It is thus clear that much further investigation of atmospheric noise is necessary, and that this must be conducted in close co-ordination with research on the propagation of radio waves through the ionosphere, a combined study which the Radio Research Board is in an admirable position to carry out. The present investigations on atmospheric noise level need considerable extension in several respects. The measurements at present in hand are made with an omni-directional receiving arrangement,

and since what is required to be known is the direction and intensity of the main flux of noise at any place and time, it is necessary to combine measurements of the field strength with those of direction of arrival on the same frequency bands in a complete study of the subject. Also, in view of the increased interest in the lower end of the radio-frequency spectrum (200 kc/s and below), for applications such as navigational aids, it will be necessary to extend the present observations downwards in frequency to a lower limit which may well be the value of about 10 kc/s adopted in the past for special research in atmospherics on account of its freedom from man-made radio signals.

(5.5) Extraterrestrial Noise

At the other end of the frequency spectrum, above 20 or 30 Mc/s, it is found that disturbance due to atmospheric noise decreases, owing partly to the relatively small energy radiated by the source at such frequencies, and partly to the limitations imposed by ionospheric conditions on the propagation of very short waves to considerable distances. The highest frequency which can be so transmitted at the present time is already known to be about 50 Mc/s on favourable occasions, and is likely to increase somewhat as we approach the forthcoming sunspot-maximum conditions in 1948–49. But the occurrence of solar activity is now known to produce another type of radio disturbance in that the sun occasionally emits radiation in the radio spectrum of an intensity greatly in excess of that which would be associated with normal black-body radiation corresponding to the temperature of 6 000° K normally assigned to the surface of the sun. This radio noise from the sun has been received in the frequency band 10–30 Mc/s, but it is then usually the precursor of a fade-out of signals in this band. This occurrence is to be expected from the fact that solar activity is often accompanied by a large increase in ultra-violet radiation, which in turn causes an increase in ionization in the lower levels of the ionosphere, with corresponding absorption of the radio waves.[51] If, however, the observing frequency is increased, the noise radiation is found to penetrate the ionosphere with only slight attenuation, and successful observations have been made recently on frequencies of about 85 Mc/s and above. But here we are embarking on the fringe of a new field of investigation which, with the aid of the techniques of very-short-wave transmission and reception developed during the war years, offers a very large scope for investigation in the future.

(6) CONTRIBUTIONS TO THE SUBJECT BY OTHER BODIES

In concluding this paper it must be emphasized that in accordance with its title the object has been to review the investigations into the propagation of radio waves conducted during the past decade by the Radio Research Board in this country. This limitation of scope has necessarily precluded much reference to other work on the subject carried out in the United Kingdom, notably by some of the organizations associated with or responsible for the operation of radiocommunication circuits or broadcasting. It is with some satisfaction that those responsible for the original conception and setting up of the Radio Research Board within the Department of Scientific and Industrial Research in this country, over a quarter of a century ago, have seen this type of organization accepted as a model for similar radio research laboratories which are now established in all the Commonwealth countries. Many of the establishments overseas corresponding to the Radio Division of the National Physical Laboratory are actively engaged in the study of the propagation of radio waves along lines comparable with those described in this paper; the workers engaged thereon are in close and frequent communication with those in the United Kingdom, and there is a free and constant interchange of programmes of work and results of investigations. Similar close co-operation has also been maintained for many years past with the National Bureau of Standards of the United States. In this manner it has become practicable to conduct research on a truly world-wide basis, a facility which is necessary for any extensive work in this field.

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